Extreme waves in Canadian coastal waters

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Abstract

"Extreme" waves are commonly defined as extremely large waves compared to the background wave field and are often called "rogue" waves. Wave buoy records off Canada's west coast reveal strong spatial and temporal variability in the occurrence rate of rogue waves with differences up to a factor three over distances less than 100 km. Strong tidal currents interact with the wave field. On the continental shelf rogue waves occur, on average, twice as frequently during strong currents compared to slack tide. In Dixon Entrance rogue wave occurrence peaks during the weakest currents. The significant wave height, characterizing the background wave field, is also strongly affected by currents. Modulations of up to 2m within one tidal cycle are observed. In coastal locations the wave field is modulated at the tidal semi-diurnal period, in deep water modulations occur at the inertial period. An important aspect, in addition to the large wave height, is the surprise effect of extreme waves. So-called "unexpected waves" are waves which are twice as large as any wave during a quiescent period of at least a few minutes duration. Their occurrence rate has been modelled based on random linear superposition and extracted from surface elevation records from waverider buoys at about 50 locations along Canada's east and west coast. Simulations are in reasonable agreement with the observations.

1. Introduction

"Extreme" or "rogue" waves continue to be a matter of concern and of broad scientific interest (Garrett & Gemmrich 2009). Comprehensive reviews are given by e.g. Müller & Henderson (2005), Dysthe et al. (2008) and Kharif et al. (2009). Although there is no unique definition of what constitutes a "rogue" wave, they are generally defined as those with a size exceeding a specified multiple of the significant wave height $H_{rogue} = \alpha H_s$, where $H_s = 4\sigma$ is the significant wave height and σ the standard deviation of the surface elevation. A common, but arbitrary, choice is $\alpha = 2.2$, although some studies use $\alpha = 2.0$. For linear theory and a narrow-banded spectrum, the wave heights follow the Rayleigh distribution and the occurrence rate of a given wave height is

$$p(H) = \frac{H}{4\sigma^2} exp\left[-\frac{H^2}{8\sigma^2}\right]. \quad (1)$$

The probability of exceedence of any height H is:

$$\int_H^\infty p(H)dH = exp\left[-\frac{H^2}{8\sigma^2}\right]. \quad (2)$$

Thus, based purely on the definition $H_{rogue} = 2.2H_s$, a rogue wave would be expected to occur about $1/16,000$, or about every 2 days for typical open ocean wave periods - not exactly a rare event. Obviously, the true concern is when rogue waves occur during high sea states. Taking

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5 hours as a typical period for the passage of the peak of a storm one would estimate that roughly 1 in 10 storms poses the risk of severe rogue waves. These estimates are based on linear wave theory; resonant non-linear interactions may generate more frequent rogue wave occurrence in wave fields with narrow directional spectra.

2. Unexpected waves

The above definition of extreme waves is solely based on the height ratio. For offshore structures the absolute size of a wave, and whether it is breaking or not, are the most significant factors for risk assessment. However, for seafarers or visitors to beaches an additional aspect is the "surprise" effect. A rogue wave occurring within a group of larger waves might be easier to handle than a wave, say, 1.8 times H_s following a more quiescent period of a few minutes duration when all waves were much smaller than the average background wave field. Thus, the "unexpectedness" of a wave, whether a rogue or not, can be just as important as the extreme height. An example of such an unexpected wave is given in Figure 1. The top panel shows a typical 20-minute record of surface elevation recorded with a waverider buoy off the NW coast of Vancouver Island (station MEDS226). The significant wave height obtained from this record is $H_s = 3.6m$. The largest wave, at $t = 451s$, has a crest-to-trough height of $H_{max} = 5.9m$, yielding $H_{max} = 1.64H_s$. Thus, if solely based on the height ratio, this record would not contain any extreme waves. Taking a shorter subsection of this record (Fig.1, bottom panel) reveals the special significance of the wave at $t = 451s$. This wave occurred at the end of a quiescent period and it is more than twice as high than any wave in the preceding 250s. Such a quiescent period of 4 to 5 minutes might be long enough for recreational boaters or beachcombers to draw their attention away from the wave field and the sudden larger wave might not be anticipated, or in other words, it might be called an "unexpected" wave.

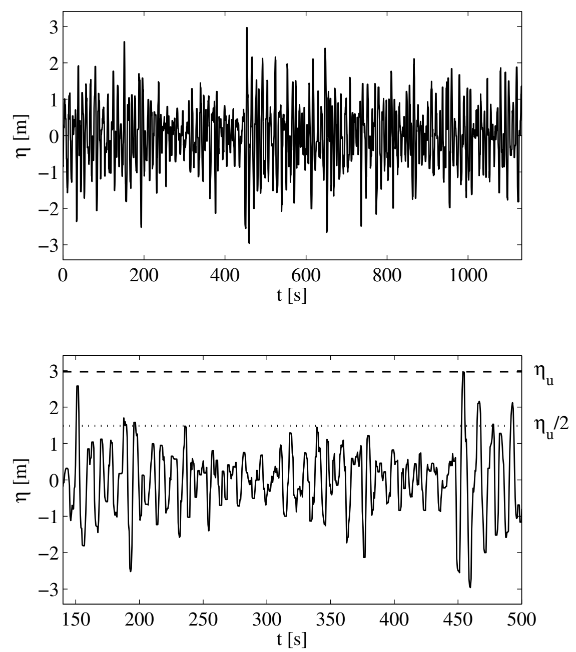

Figure 1: Surface elevation time series recorded off Cape Scott, BC (MEDS226). Top: entire 20 minute record. Bottom: 360s long data interval taken from the record. The dashed line indicates the amplitude η_u of an "unexpected" wave at t=451s; the dotted line depicts half its amplitude.

Gemmrich & Garrett (2008) performed Monte-Carlo simulations, based on random linear superposition for deep water waves, and found that waves with an amplitude twice as high as any wave during the previous 30 wave periods occurred about 1 in 14,000 waves. In a follow-on study (Gemmrich & Garrett, 2009) the simulations were extended to intermediate water depths. The occurrence rate of unexpected waves increases with decreasing normalized water depth kh, with wave number k and local water depth h, because of the increased amplitude of the non-resonant phase-locked second harmonic. At $kh = 1$ "unexpected" waves occur about three times more frequently than in deep water. The enhancement factor increases to 8 at $kh = 0.6$. Thus, in shallow coastal waters an "unexpected" wave would be expected about every 3 hours. Analysis of historic surface elevation records from Canada's east and west coasts (Figure 2) show reasonable agreement between observations and simulations (see also Gemmrich & Garrett, 2009). Simulations for the east coast records are all within a factor 2 compared to the observations. In the Strait of Georgia (west coast) "unexpected" waves occur up to 4 times more frequent than the simulated values. The area has strong tidal currents and the simulations did not include wave-current interactions. However, the effect of currents on the occurrence rate of "unexpected" waves has not been analyzed, yet.

We emphasize that "unexpected" waves defined in this way are not necessarily the largest waves in a record and they are unlikely to be rogue waves that exceed some specified large size threshold. We should also stress that by an "unexpected" wave we mean a wave that is not anticipated by a casual observer, though clearly such unexpected waves are expected in a statistical sense.

3. Extreme wave heights

Wave conditions off British Columbia have been monitored routinely since the early 1990's. Hourly records of wave and wind parameters exist for 10 offshore and coastal locations and the data are quality controlled and archived by the Integrated Science Data Management (DFO-ISDM), formerly known as MEDS. In particular, significant wave height H_s and maximum wave heights H_{max} are extracted from a 37 minute long record. Only the maximum crest heights are measured and the reported H_{max} are taken as twice the maximum crest elevation η_{max}. This operational definition of H_{max} neglects nonlinear effects on the wave form and is likely to overpredict the true maximum trough-to-crest wave height.

We extracted the occurrence rates of rogue waves from these data records (Fig.3). For practical purposes, we registered a rogue wave event when

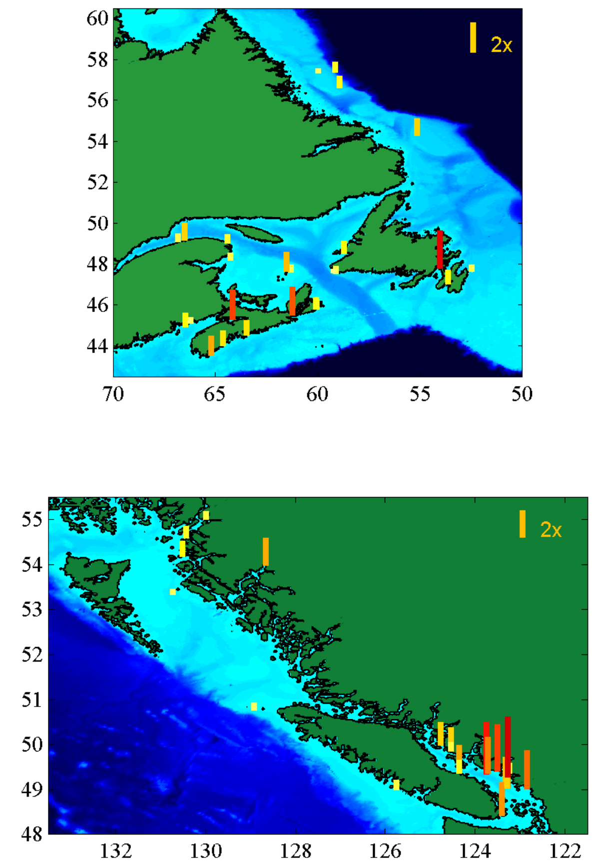

Figure 2: Observed normalized occurrence rate of "unexpected" waves. Occurrence rates are normalized by linear simulations, allowing for the phase-locked non-resonant second harmonics (see Gemmrich & Garrett, 2009). Length and colour of the bars are proportional to the normalized occurrence rates. Values larger than 1 indicate "unexpected" waves observed more frequently than obtained by the simulation. Top: East coast Canada, bottom: West coast Canada.

$$H_{max} \geq 2.2H_s \;\text{ and }\; H_s \geq \overline{H_s} \quad (3)$$

are fulfilled, where $\overline{H}_s$ is the median value of H_s for the entire station record. Thus, rogue waves in low sea states are not considered. The data set records only one maximum wave height for every hourly record and any additional waves with $H \geq 2.2H_s$ in the record would not be detected. Strictly, the operational maximum wave height definition applied by ISDM implies an equivalent rogue wave definition $\eta_{max} \geq 1.1H_s$, although the more common criterium is $\eta_{max} \geq 1.25H_s$ (Dysthe, et al. 2008).

There is a clear trend of higher rogue wave occurrences towards coastal locations (Fig.3). Locations exposed to the open Pacific experience about 100 such rogue waves per year. However, in more coastal waters the occurrence rates are 1.5 to 4 times higher. The extreme low rate recorded at the three offshore locations is puzzling but might be related to the fact that these three stations are 6m Nomad buoys, and all others are 3m discus buoys. All stations are in at least 220m water depth, except C46183 (62m) and C46206 (73m).

The wave fields undergo a significant transition between the open ocean and the Queen Charlotte Sound. An example of a storm passage is given in Fig.4. During the two wind events, on Jan 28 and on Jan 31–Feb 2, the wind direction was from the south and the speed reached 15 m/s. Station C46185 is almost directly downwind from C46207, whereas C46147 is about the same distance but to the NW. The evolution of the wave field at the two open ocean locations (C46207, C46147) is quite similar, and so is the rogue wave occurrence rate (3 events at C46207, 4 events at C46147). However, in South Hecate Strait the growth of the wave field is much more rapid and the rogue wave occurrence is 4–5 times higher. The question arises what causes these significant differences in rogue wave occurrence across relatively short distances?

4. The role of currents

Here we present some evidence that wave-current interactions may play a significant role in generating this highly inhomogeneous rogue wave behaviour, although local topographically-induced inhomogeneity in the wind field and refraction in shallow water may also be important. The currents at the locations in the Queen Charlotte

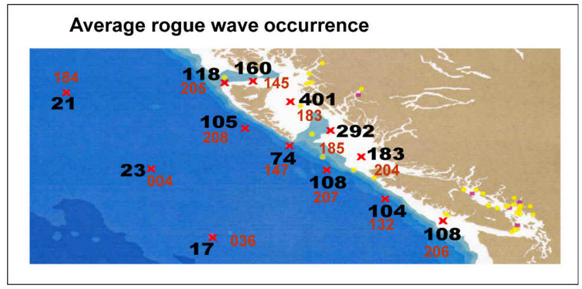

Figure 3: Rogue wave occurrence observed at operational wave buoys along Canada's west coast. Black numbers give the average number of hourly records with $H_{max} \geq 2.2H_s$ per year. Data are limited to high sea states only. Red numbers are the station identification C46xxx.

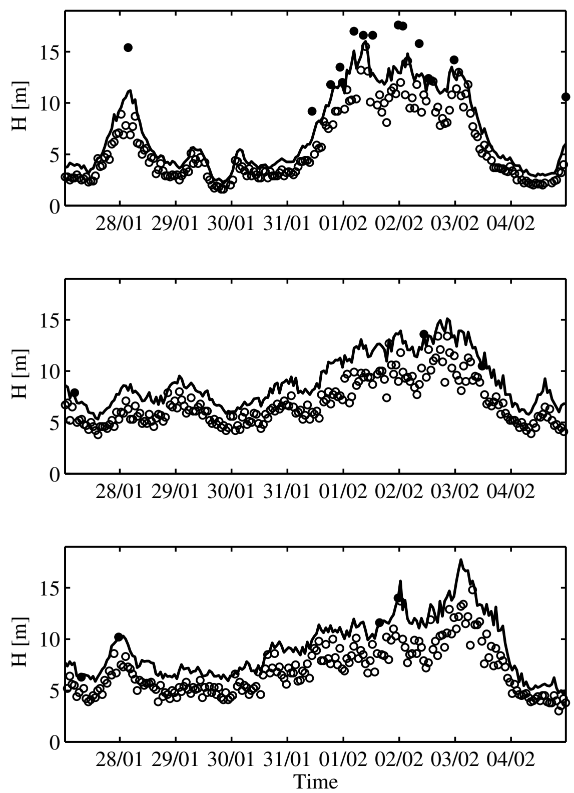

Figure 4: Wave record during the passage of a storm in Jan–Feb 2001. Shown are the maximum wave height (circles) and the significant wave height times 2.2 (line). Rogue waves are shown as solid circles. Top: Data from C46185 (South Hecate Strait), middle: C462007 (East Dellwood), bottom: C46147 (South Moresby).

basin (C46145, C46183, C46185, C46204) are fundamentally different from the currents at all the other locations (those exposed to the open Pacific). In the coastal regions semi-diurnal tidal currents of up to 1 m/s occur (Foreman, 1978), whereas tidal currents along the outer shelf are only a few cm/s. In areas with weaker tidal currents, wind-induced inertial currents are dominant. These currents are less regular (and less predictable) than tidal currents but can reach similar magnitudes. In both cases, these surface currents interact with the wave field. The power spectra of the time series of the significant wave height in Dixon Entrance shows a clear peak at the semi-diurnal period (Fig.5). This energy is not related to the local wind forcing, since the wind record does not have any elevated energy at the semi-diurnal period, but is the result of interactions between the waves and the semi-diurnal tidal currents. This interactions affects the maximum wave height in a slightly different way than it affects the significant wave height, as indicated by the small peak in the spectrum of H_{max}/H_s (Fig.5, middle panel). Station C46206 is exposed to the wind and wave fields of the open Pacific and dominant tides are diurnal with maximum currents reaching 0.35 m/s. The power spectra of the wave field show no indication of tidal currents interacting with the wave field at this location (Fig.6). However, the peak in the H_s power spectrum at a period of 16 hours corresponds to the inertial period at this latitude, suggesting modulations of the wave field by inertial currents.

Currents are not measured by the wave buoys and no direct current observations exist at these locations. However, barotropic tidal currents in the area are well predicted (Foreman, 1978), and the spectral content of H_s in Dixon Entrance (Fig.5) indicates tidal currents as the dominant factor at this location. Tidal currents are almost entirely in the E-W direction and are therefore roughly parallel to the propagation of waves from the open Pacific. We filtered the H_s time series with a median band-pass filter, centered at $12h$ period. The median filter is a nonlinear technique that applies a sliding window to the data sequence. It has the advantage of a weak cut-off response (Fig.5, top panel), and, more important, it preserves abrupt changes without introducing artificial ringing effects. Fig.7 shows a 10 day segment of modulations of significant wave height overlaid on the tidal currents. Wave height fluctuations of up to 1.6m during a 12 hour period are observed, corresponding to a 46% change in

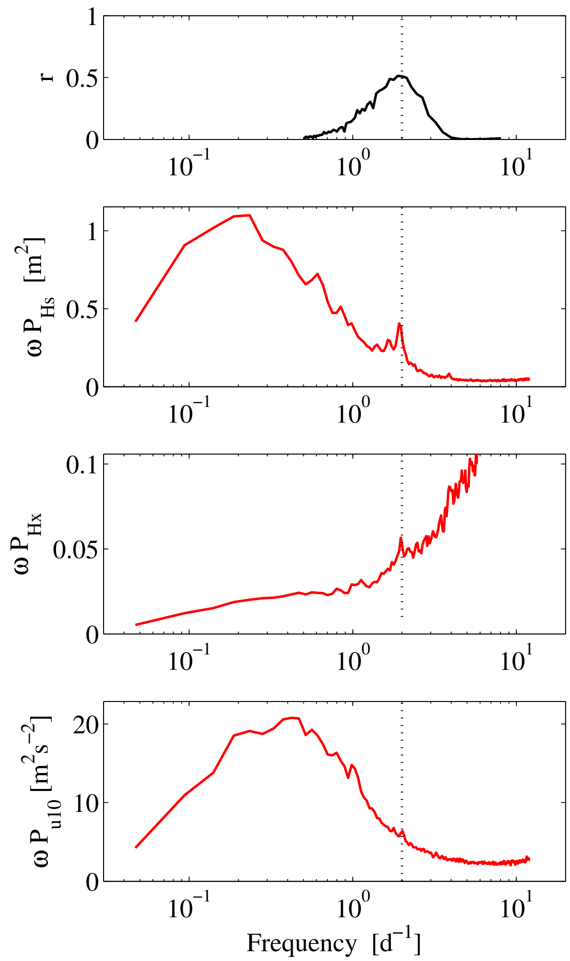

Figure 5: Spectra of significant wave height (2^{nd} panel), normalized maximum wave height H_{max}/H_s (3^{rd} panel) and wind speed (bottom) for data recorded at C46145 (Central Dixon Entrance). The dotted line corresponds to the dominant tidal period (semi-diurnal). Top: Response curve of the median band-pass filter.

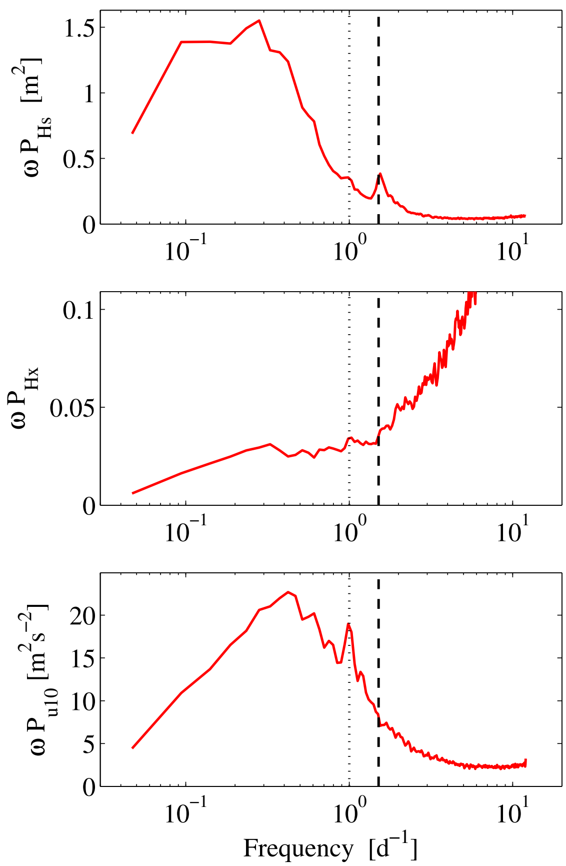

Figure 6: Spectra of significant wave height (top), normalized maximum wave height H_{max}/H_s (middle) and wind speed (bottom) for data recorded at C46206 (La Perouse Bank). The dotted line corresponds to the dominant tidal period (diurnal), the dashed line to the inertial frequency.

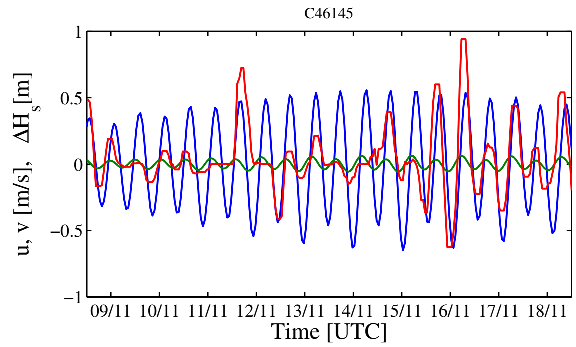

Figure 7: Modelled tidal currents u (eastward, blue line), v (northward, green line) and bandpass filtered significant wave height ΔH_s (red line) in Nov. 1993 at C46145 (Central Dixon Entrance).

H_s. Waves are larger during currents towards East, that is when wave propagation and currents are in the same direction, and smaller during the tidal phase of opposing currents. The observed wave-current relation shown in Fig.7 is typical for this location and, in particular, the observed phase relation holds throughout the entire record.

The theoretical framework for wave-current interactions is based on the conservation of wave action (Bretherton & Garrett, 1968):

$$\frac{\partial A}{\partial t} + \nabla \cdot \left[(\mathbf{c_g} + \mathbf{U})\, A \right] = 0, \tag{4}$$

where $\mathbf{c_g}$ is the wave group velocity, $\mathbf{U}$ the current velocity, and the wave action $A = E/\sigma$ is the wave energy density E divided by the intrinsic wave frequency σ. Depending on the properties of the current compared to the wave parameters various modifications of the wave field may occur. Maybe the most familiar wave-current interaction occurs for wave propagation from still water into an opposing, stationary current, such as waves propagating into a river estuary: waves steepen and get shorter until they reach a location where the current speed U reaches a quarter of the wave phase speed c, where the waves collapse due to wave breaking. A weak inhomogeneous opposing current $|U| < c/4$ focuses the wave energy, resulting in wave heights that are larger than the height of the incoming wave field in the absence of currents. Here we consider the case of a large scale wave field interacting with tidal currents on the continental shelf. Somewhat surprisingly, tidal currents and wave height fluctuations are in-phase. This phase-relation is possibly due to a time-dependent, homogeneous tidal current interacting with a nearly 1-dimensional wave field, as discussed by Tolman (1990), but more likely due to 2-d effects. The phase relation between wave modulations and tidal currents observed in Dixon Entrance is consistent with Tolman's (1990) quasi-homogeneous approximation. However, the predicted relative change in amplitude is only about 1% - much less than the observed change of amplitude. Moreover, this approximation depends on the unlikely assumption that the tidal currents do not vary on a scale smaller than the tidal wave length.

An alternative explanation could be focusing of wave energy due to wave refraction. Garrett (1976) looked at surface waves propagating obliquely through a surface current pattern $(U(y), V(y))$ as a generation and feedback mechanism for Langmuir circulation. However, the theory can also be applied to waves propagating into a large scale, horizontally sheared surface current $U(y)$. The relative change of wave energy is a strong function of θ, the angle between wave and current propagation, and, to a lesser degree, the maximum normalized current speed $U^* = U(k_0/g)^{1/2}$, where k_0 is the wave number in x-direction in still water:

$$\frac{E}{E_0} = B\, sin\theta \left[1 - \left(\frac{cos\theta}{B}\right)^2\right]^{-1/2}, \; B = (1 - U^*\, cos\theta)^2 \quad (5)$$

This approximation gives positive enhancements for waves following within an oblique angle of ±45° and reduction of wave energy for opposing currents at ±45°. For small angles θ (the exact values depend on U^*) internal reflection occurs and the theory is not applicable. For the conditions in Dixon Entrance a 45% relative increase of wave amplitude is predicted for $\theta = 20°$ and a 10% decrease for opposing currents at 20°. This is of the same order as the observed amplitude modulations.

Fig.5 shows a semi-diurnal signal not only in the significant wave height, but also in the normalized maximum wave height. To test for a potential relation between rogue wave occurrence and tidal phase, we conditionally sample the rogue wave occurrences, as defined by (3), with respect to the phase of the tidal current component parallel to the wind (and assumed wave) direction. The hourly wave records (H_s and H_{max}) were sorted into 11 bins according to the hourly mean speed of the tidal current. Only the velocity component parallel to the wind, which is assumed to be the dominant wave direction, is considered. The bins are site-specific, spanning the observed range of tidal speeds at a specific location. For each bin the fraction P of rogue waves is then calculated and shown in Fig.8.

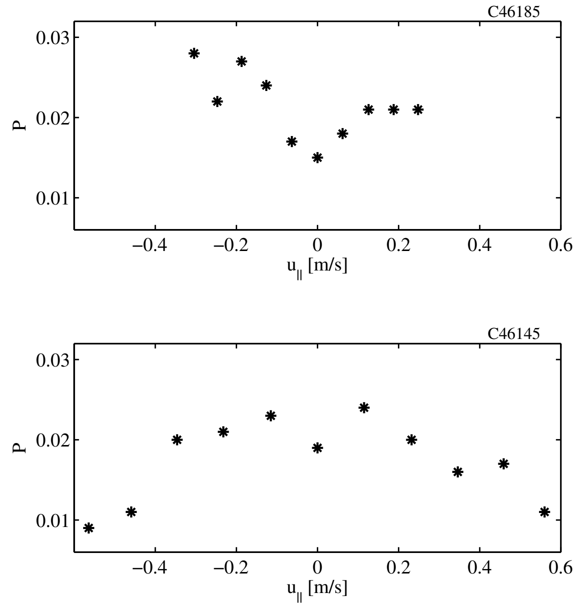

Figure 8: Rogue wave occurrence P as function of tidal current $u_{||}$ aligned with the wind (and assumed wave) direction. Top: C46185 (South Hecate Strait), bottom: C46145 (Central Dixon Entrance)

Rogue wave occurrences are phase-locked to the tidal current and modulations of up to a factor 3 are seen. In the Queen Charlotte Sound (*e.g.* C46185) rogue waves are most frequent during periods with the strongest opposing currents. The smallest probability of rogue wave occurrence is during slack tide. A qualitatively similar behaviour is found in Hecate Strait (C46183, not shown). However, in Dixon Entrance the opposite phase relation is found, with rogue waves being 2 to 3 times more likely during weak currents than at strong opposing or following currents (Fig.8).

5. Conclusion

Many of the hourly records of wave and wind field parameters from operational Canadian wave buoys extend now over periods of 15 to 20 years. These records provide an opportunity to study regional distributions and properties of large and extreme waves. Here we have focused on the west coast of Canada. Occurrence rates of rogue wave increase towards more coastal locations. Surface currents, both tidal and wind-induced inertial currents, have a strong effect on the background wave field as well as on rogue wave occurrences. Not all aspects of wave-current interaction are yet fully understood. In addition to the large wave height of extreme waves, the surprise effect of waves that are large compared to the wave field of the previous few minutes might also be important. Long records of surface elevation are needed for the assessment of these so-called “unexpected” waves.

Acknowledgments

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